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Applications of Tethers in Space

Executive Summary

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PREFACE

The 1983 Applications of Tethers in Space Workshop was an important forum for diversity of scientific and engineering opinion about the prospective uses of tethers in space. The technical arguments, given in the resulting Workshop Proceedings, supporting the development of the Tethered Satellite System are carefully reasoned and thoroughly sound. The scientific uses of the new facility are striking in their importance and breadth. Overall, we are very impressed with the sheer enthusiasm which pervades the entire document. It is clear that this cooperative U.S./Italian project has struck many resonances with a broad range of potential users of space platforms.

In fact, we wonder if the support given to the Tethered Satellite System isn't an expression of technical pleasure derived from the quickening pulse of mankind's ability to explore and utilize space. The opportunity to conduct operations from multiple platforms orbiting Earth can be viewed as another liberation step in our ability to move freely throughout the solar system and, perhaps, even into deep space.

The presentations contained within the Workshop Proceedings consider many different applications. Some of the topics are clearly more mature, in a technical and scientific sense, than others. Yet, this is the time to have speculative thoughts and novel ideas. The passage of time and confrontations with technical and fiscal reality will winnow the collection into a harvest of rich technical productivity.

We commend these proceedings to the reader as an important document demonstrating both current engineering and scientific perceptions concerning tethers in space and as a guide to many ideas whose time will come in the future.

Peter Banks
Carlo Buongiorno
1 December 1983

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FOREWORD

The "Applications of Tethers in Space" Workshop was held at Williamsburg, Virginia, on 15-17 June 1983. The workshop was sponsored by the Office of Space Flight (OSF) and Marshall Space Flight Center (MSFC) of the National Aeronautics and Space Administration (NASA). The goals of the workshop were:

- To provide a focus for, and a review of, technological opportunities and requirements for the application of tethers in space.
- To brief aerospace planners and specialists on the nation's space program plans for the Tethered Satellite System (TSS) and on NASA's current efforts for developing effective tether applications.
- To delineate a data base of methods, techniques, and technologies which may prove effective in the design and development of tether systems for use in the space program.
- To aid in planning OSF's tether applications program by identifying applications, technological needs and promising research topics and approaches.
- To insure that all parties involved are aware of significant programs in industry, academia, government and the international community which may be helpful in determining optimal tether roles for future space missions.

The workshop served to continue the dialogue between the tether community and the space program's planners, researchers, and operational staff. The focus for continuing this dialogue will be a tether research program which is being supported by NASA's Office of Space Flight to begin in 1984. The goal of the research program is to develop an empirical data base for determining application optimal roles, procedures, and interfaces for a tether space program. This includes ground operations as well as on-orbit operations.

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This report summarizes the work of the Workshop panels which is reported at length in the Workshop Proceedings, published separately in two volumes. Conclusions and Recommendations are made concerning NASA's multi-year "Applications of Tethers in Space" study program.

1 December 1983
Washington, D.C.

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SECTION I

INTRODUCTION

A variety of space applications involving two bodies connected by a tether have been proposed in recent years. Retrieval of stranded astronauts by "throwing a buoy on a tether" from a rescue vehicle to an astronaut and then reeling the tether back to the rescue vehicle was such a consideration in the early 1970s. Another early tether application was studied involving a tethered (rather than hard docked) interface between the Apollo Telescope Mount (ATM) and the Skylab Orbital Workshop. Conceived as a means of station keeping between the two bodies while isolating the telescope from the anticipated disturbances of the manned workshop, this approach was found unattractive because of the difficulties in precisely determining and controlling the tension forces to be applied to the tether and in providing the constant manned supervision which would be required to ensure flight safety. Two successful orbital space flights, Gemini XI and Gemini XII, involved tether experiments in which a manned Gemini space vehicle was tethered to an unmanned Agena vehicle. The Gemini XI flight demonstrated a rotating configuration in which the Gemini spacecraft was tethered to the Agena by 30.48m (100 ft.) of polyester webbing. Centrifugal force maintained tension in the tether following spin-up of the configuration using the Gemini thruster reaction control system. The Gemini XII flight demonstrated a gravity gradient stabilized configuration.

During recent years, the advent of the Space Shuttle has spawned a number of innovative concepts for using tethers in space. One, involving a scientific satellite for atmospheric and electrodynamic research, has been approved by the Administration as a program that will lead to flight in 1987. This program is a cooperative activity between the U.S. and Italy, called the Tethered Satellite System (TSS) and dates back to 1974 when Professor G. Colombo of the Smithsonian Astrophysical Observatory submitted a proposal for study and subsequent development of a space tether system. Subsequently, numerous studies were performed by NASA, academic institutions, and various aerospace contractors to verify the engineering feasibility and scientific merit of the proposed system.

An important milestone in the development of the tethered satellite program was the final study report of the Tethered Satellite Facilities Requirements Definition Team, composed of leading scientists and engineers from the U.S. space research community. This report identified numerous, new topics of scientific study which would benefit greatly, and often uniquely, from the tethered satellite concept. The report also provided, for the first time, an evaluation of the system resources and parameters needed to support the broad range of scientific studies which would be possible with the tethered satellite system.

In December 1982, NASA/MSFC competitively awarded Martin Marietta Denver Aerospace the first of a two-phase contract leading to a tethered satellite initial mission currently scheduled for December 1987. This program will be performed as a cooperative development between NASA and the Italian Council for National Research. The first phase of the program, which is devoted to breadboarding critical hardware elements of the system and establishment of interfaces with the Italian co-developer, Aeritalia, will conclude in December 1983. The flight hardware development program, will commence in January 1984 in the U.S. and in April 1984 in Italy.

Current plans for the initial mission of The Tethered Satellite System (TSS) call for the deployment of a satellite upward from the Shuttle 20 kilometers on a conducting tether to measure electromagnetic interactions within the Space Plasma and verify the operation of the TSS.

Follow-on missions are anticipated which would deploy the tethered satellite downward as well as upward to conduct scientific research remote from the orbiter and in hitherto inaccessible regions. Areas of scientific research include:

- Investigations of space plasma phenomena using a conducting tether
- Investigations of atmospheric and ionospheric composition and physical behavior at 130 to 150 kilometer altitudes

- Performance of high resolution measurements of magnetic field and geopotential properties of the earth.

Potential future applications of the many capabilities of space tethers are limited only by man's imagination. The "Applications of Tethers in Space" workshop was conceived as a means of stimulating new ideas concerning space tethers and critically examining current concepts for future tether applications. The purpose of the workshop was to inform a broad spectrum of aerospace professional groups of NASA's "Applications of Tethers in Space" planning progress and to infuse their collective imagination, experience and guidance into the development of a multi-year Tether Applications Program Plan. Over the course of this multi-year plan, each tether application will be reviewed for:

- Scientific and engineering significance
- Theoretical feasibility
- Engineering design feasibility
- Requirements and cost effectiveness potential
- Preliminary design and concept verification validity

This should lead to proof of concept testing beginning as early as FY 1986.

The objectives of the "Applications of Tethers in Space" workshop were as follows:

- Identify potential applications for tethers in space.
- Develop a first order assessment of the feasibility and benefits of tether applications.
- Recommend future actions necessary to enable tether applications, including required technology advancements.
- Stimulate industry and government planners to consider the unique properties of tethers in designs for future missions.

The workshop was organized into six parallel panels co-chaired as follows:

Panel	Co-Chairmen
Electrodynamic Interactions	Nobie Stone (MSFC) Richard Taylor (Smithsonian)
Transportation	Max Hunter (Lockheed) Ernesto Vallerani (Aeritalia)
Artificial Gravity	George Butler (MDAC) Robert Freitag (NASA HQ)
Constellations	Giovanni Rum (PSN/CNR) Frank Williams (Martin-Marietta)
Technology and Test	Col. Norman Lee (USAF) Paul Siemers (LaRC)
Science/Applications	Robert Hudson (NASA HQ) Franco Mariani (University of Rome)

The goals of each panel were:

- Identify new applications for tethers in space
- Analyze and critique all identified tether applications relative to their practicality, cost benefit, and operational requirements
- Identify those critical design, performance, or operational factors that must be included in the evolution of the practical feasibility of each tether application
- Provide recommendations to NASA for the continued evaluation and definition of the tether applications identified.

The first day of the workshop began in plenary session with a keynote address on the evolution, application and utility of tethers. This was followed by presentations on the Tethered Satellite System, a tutorial session on tether fundamentals, and six lectures that surveyed applications and technology of tethers in space. The plenary session was followed by dinner with guest speaker Prof. Giuseppe Colombo discussing "Where are we going with Tethers?".

On the second day, the participants divided into six working panels: Electrodynamic Interactions; Transportation; Artificial Gravity; Constellations; Technology and Test; and Science Applications. Each panel examined the theoretical and practical feasibility of each tether application identified for evaluation. In the late afternoon, each panel summarized its preliminary findings and recommendations. On the third morning, the panels met in separate sessions to revise and write up their final findings and recommendations. These reports were presented to the entire workshop meeting in plenary session in late morning. The workshop attendees dispersed after lunch with the exception of the panel co-chairmen. The panel co-chairmen convened after lunch and wrapped up their final reports for editing and publishing at length in the Workshop Proceedings and summarized in this volume.

SECTION II

SUMMARY OF PANEL REPORTS

SPACE SCIENCE AND APPLICATIONS

I. INTRODUCTION

Space Science and Applications has had an historical interest in the Tethered Satellite System (TSS) from its inception. The original proposal, by Columbo et al. (1974) entitled "Skyhook", was to carry out space science experiments at low altitudes. Thus, a most important aspect of future missions in the area of Space Science and Applications is for the reflight of the present satellite system to obtain additional scientific information.

The deliberations of the panel were broken down into five main subheadings: (1) the exploitation of the present system and the need for repeat missions, (2) multiple payloads placed along the tether, (3) the extension of the present altitude limit to below 130 km, (4) the development of tethered autonomous multiplets for studying both the Earth's atmosphere and ionosphere and also for studying the planets, and (5) a subtether. The panel did not consider space plasma physics in any depth, as this area of research was covered by the Electrodynamics Interactions panel.

II. EXPLOITATION OF PRESENT SYSTEM

Reflights of the present TSS configuration would involve no significant change to the launch and retrieval mechanism as presently conceived. Only minor changes to the satellite are envisioned. Four areas of research were identified.

(1) Aeronomy studies using the same instrumentation provided for the second mission. This instrumentation will be reflown in different orbital inclinations, for example, 28°, but at a different local time of the ascending mode, and/or a different season. Another set of missions would involve reflights in polar orbit. A particle spectrometer could be added to the payload complement in order to obtain significantly new information. The length of the magnetometer boom would have to be increased and a second fluxgate magnetometer could be installed.

(2) Gravity and magnetic potential mission. The TSS satellite body stripped of the aeronomy experiments could be used to fly both below and above the shuttle to obtain information on the magnetic field of the Earth. The satellite would need to have a magnetometer boom at the end of which would be placed two magnetometers, one scaler, and one vector. This experiment would require a high precision altitude determination (GPS or similar direct measurement). A gravity gradiometer could be flown inside the spacecraft sphere and calibrated to the altitude reference point. It would also be desirable to place corner reflectors on the spacecraft for laser ranging from the shuttle or from the ground.

(3) Mapping and remote sensing. The tethered satellite has the ability to place optical instruments at much lower orbital altitudes than can be presently achieved. There is the possibility, therefore, that much greater spectral or spatial resolution can be attained even with existing insruments. This area of work has not been actively investigated to date, and the panel felt that this was an area that should be examined and studied in the future.

(4) Advanced sensors for geodynamics. Superconducting technology offers the promise of dramatically increased sensitivity and accuracy in magnetic and gravitational measurements. A very sensitive magnetic gradiometer could measure signals from the earth's core and crustal field, while cancelling most of the interference from external sources. The satellite would carry a space dewar containing liquid helium coolant for the superconducting vector magnetometer and magnetic and gravity tensor gradiometers. The entire satellite should be as non-magnetic as possible, with any essential magnetic sources physically separated from the sensor package. The tether would isolate the sensor from magnetic and gravitational interference from the space shuttle. The orientation of the sensors should be measured as accurately as possible. Future TSS missions incorporating such advanced magnetic and gravitational sensors, if flown periodically, would allow precise long term monitoring of the terrestrial magnetic crustal signatures and the geologically related gravitational gradients.

III. MULTIPLE PAYLOADS

Three applications of more than one satellite being placed on the same tether at the different altitudes were also identified:

(1) Aeronomy. One of the difficulties in ionospheric and atmospheric research is the inability to detect changes in atmospheric composition which are due to temporal effects from those due to spatial effects. A single satellite moving through the atmosphere cannot, in general, detect these changes. What is required are several satellites moving in approximately the same altitude or spatial region. These satellites could either be strung along a tether released from the shuttle, or could be tethered together in a free-flying mode. Such satellites would contain mass spectrometers, devices to measure wind direction, density determinations, instruments to obtain ion and electron temperature, and instruments to determine the composition of the ambient ions.

(2) Geodynamics. A multispacecraft tether could be used principally for the measurement of gravity and magnetic field gradients. These measurements can be made both upward and downward from the shuttle. The upward tethered satellite could make measurements of the core magnetic field, whereas the downward tethered satellite could make measurements of local anomalies.

(3) Remote Sensing. For many sensing measurements of the Earth, different angles of observations are required. The reflectivity, emissivity, and scattering properties of surfaces are strongly dependent on the angle of viewing and it has been shown that by making observations at different angles, more information can be obtained from the scattering surface than from a single angle. The proposed new tether application could obtain different angles of observation by placing instruments at different altitudes along a tether, e.g., the shuttle could house one set of instruments while the tethered satellite could have a similar set at 100 km below the Shuttle. Both sets of instruments could view the same point on the ground, but with different viewing angles.

IV. LOWER ALTITUDE MEASUREMENTS

An important attribute of the Tethered Satellite System is its ability to deliver payloads or instruments to lower altitudes than can be achieved by free-flying satellites in stable orbits. This capability can be applied to a wide range of scientific disciplines. In geodynamics, the measurements of the Earth's gravitational and magnetic fields can be greatly improved by global observations at altitudes closer to the surface of the Earth. For remote sensing, the resolution of the measurements can be improved. In aeronomy, many of the most important processes that take place in the upper atmosphere occur in the altitude region between 90 and 130 km.

Deployment of a tethered satellite to about 130 km altitude is feasible. Below this, however, the exponentially increasing atmospheric density quickly increases the drag forces and consequent heating of the satellite and the tether. There is some concern that the satellite would be unable to penetrate to lower altitudes, possibly tending to skip along the atmosphere when the drag becomes too large. Design of lower altitude satellites will require special attention, and innovative ideas will be required. Possible solutions to these problems are to: (1) optimize the present tethered satellite design to fly lower altitude missions including additional thermal shielding; (2) study the advantages of flying the tether and satellite at 130 km altitude over the pole, thus bringing the satellite to 115 km altitude at the equator; (3) consider a completely new design. A nacelle shaped satellite, for example, where the atmospheric flow inside the throat could be sampled might be a useful approach. At about 120 km the mean free path of the atmospheric flow becomes equal to the dimensions of a typical spacecraft. To study this region, different experimental approaches and different interpretations will be required. Consideration could be given to the lowering of a sub-satellite from the main tethered satellite, perhaps with only a single instrument, to sample the atmosphere below 120 km.

V. TETHERED AUTONOMOUS MULTIPLETS

Although the period of time in a Shuttle mission is adequate for many scientific studies, the length of the mission should be extended in order that synoptic analysis of processes in the atmosphere can be achieved. This would require the development of autonomous multiplets of satellites joined with tethers.

A particular application of this technique would be in planetary missions in which detectors could be placed as close to the surface as is reasonable yet the main spacecraft could be placed at an altitude where slight anomalies in the planetary geomagnetic field would not send the satellite into the planet's surface. This type of mission would appear to be feasible only for planets with little or no atmosphere, but the increase in the resolution of magnetometers and gradiometers would be considerable.

For aeronomy studies, two modes of multiplet mechanics are foreseen. In the first, two spacecraft could be placed about one scale height apart, one vertically beneath the other. In the second mode, the total system would spin around the center of mass of the two spacecraft. In this mode continuous sampling of the altitude profile of the atmosphere or ionosphere could be made. This system would enable effects due to temporal and spatial variability of the atmosphere or ionosphere to be separated.

VI. SUB-TETHER

There are important applications to atmosphere physics, in which a sub-tether aboard a satellite tethered to the shuttle would enable a small sub-satellite to be deployed downward or upward from the main satellite. Vertical structure of the atmosphere could be studied in detail if such a system were available. Previous studies of vertical structure have relied on two satellites in independent orbits, or on the precession of one satellite. It is difficult in either of these cases, to separate spatial from temporal variations. Knowledge of vertical structure near the tethered satellite would allow information to be determined concerning the diurnal variations at the tropopause altitude, the nature of the temperature vari-

ations, variability associated with waves, windshear and a number of other parameters. Measurements of the vertical structure at these altitudes is fundamental to defining this region.

The sub-tether could also be used to release an inflatable passive sphere. By radar-tracking the sphere, the neutral density of the atmosphere, down to an altitude of 80 km, could be obtained. Release from a tethered satellite would allow density profiles to be derived in regions inaccessible to sounding rockets sensors, as well as near the re-entry path of the Shuttle vehicle, and in regions where density measurements are needed for the Aero-assist program, etc.

ELECTRODYNAMIC INTERACTIONS

I. INTRODUCTION

The panel considered a range of scientific and technological uses of the electrodynamic tether, identified eleven areas of particular concern, and made specific recommendations on the research required in electrodynamic interations in the immediate future.

The panel was particularly impressed by the wide range of opportunities provided by the electrodynamic tether to more fully understand the generation of waves in plasmas, the behavior of field aligned currents, the behavior of large body shuttles and wakes, and the simulation of processes (the electrodynamic tether is a solar system and astrophysics plasma simulator). Study and experimentation of the electrodynamic tether can provide a rich yield of new scientific results with potential applications to operations in space of highly significant value.

II. APPLICATIONS OF ELECTRODYNAMIC TETHERS IN SPACE

Applications identified and recommended by the panel for further investigation are listed below.

A. TECHNOLOGY APPLICATIONS

1. Tether Power Generation

The electrodynamic characteristics of a conducting tether in earth orbit can be utilized to generate useful electric power for a number of applications. The tether generates a voltage proportional to its length. This is obtained from the qV x B electromotive force, and at the expense of vehicle velocity. Therefore, it is necessary to use some means of propulsion to reboost the vehicle periodically.

The tether power generator, however, has several advantages over conventional power sources. For example, it is 2.5 to 3 times as efficient as the best possible fuel cells in terms of fuel utilization, and it is not subject to day/night cycles as are all solar arrays. The required reboost forces are so small that on a manned space station, the orbit can be maintained by using a resistojet fueled with life support effluent.

2. Tether Thrust Generation

The electrodynamic characteristics of an orbiting conducting tether can also be utilized to generate thrust. This is essentially the reverse of the power generation process (similar to a motor/generator). In this case, current is forced, by an external power source, against the emf and a force is created by $\vec{I} \times \vec{B}$.

It should be noted that the $\vec{I} \times \vec{B}$ force is not always aligned with the orbit track. In general, the angle between $\vec{V}_o$ and $\vec{F}$ varies as the angle between the tether and the geomagnetic field changes around the orbit. However, it is possible to select portions of the orbit so that the alignment is at the desired angle. This fact can be used to attain not only raising or lowering the orbit, but also to change the inclination of the orbit.

The thrust generation capability of the electrodynamic tether is not limited to use in earth orbit; it may also be useful for interplanetary travel and breaking for planetary encounter.

3. In-Plane Sheet Plasma Contactor

As an alternative to metal balloons and plasma contactors, the use of flat metallized panels could be considered. Such a contactor could be based on the well developed Heliogyro blade design and would be deployed by gravity gradient rather than rotation.

Dual edge tendons and spreader bars would support the panels normal to field lines, and parallel to the orbital velocity vector to keep aerodynamic drag low in low inclination orbits.

4. Thrust Generator for Planetary Capture

In lieu of chemical propulsion, use of a conducting tether for electrodynamic braking for planetary orbit insertion should be considered. A spacecraft designed in halves would be separated upon planetary approach while remaining connected by a conducting tether used in the thrust mode. Upon capture, the spacecraft halves would be rejoined for normal orbital operations. This approach is probably applicable only to planets with

relatively strong magnetic fields, and further study is required to assure that sufficient braking is available for capture in a single pass.

5. Use of Electrodynamic Tethers for Interplanetary Transportation

The solar wind is a magnetized plasma that flows radially outward from the sun with a velocity of about 400 km/sec. More than a decade ago, Alfven (1972) proposed that the motion of this magnetic field could be used as a propulsion source for interplanetary spacecraft. Because the solar wind magnetic field is 5×10^{-5} Gauss, the electric field seen by an interplanetary spacecraft is 2 V/km. Alfven suggested that a spacecraft with a long electrodynamic tether (say 500 km) could be proposed by the $\vec{I} \times \vec{B}$ force on the tether, or could use the power extracted from the solar wind as an energy source for ion thrusters. In principle, such a spacecraft could accelerate to the solar wind velocity of 400 km/sec.

6. ULF/ELF Communications Antenna

Use of a conducting tether for communications in the ULF/ELF bands is an attractive potential application requiring further study and experimentation to demonstrate its effectiveness. Such antennas could be self or externally powered. Communication rates are low (about 100 bits/min) but the transmissions will propagate easily through sea water or the ground. Recent studies have revised the understanding of the propagation mechanisms at these frequencies. Further studies are required to identify an approach to optimize these mechanisms for communication purposes.

B. SCIENTIFIC APPLICATIONS

The electrodynamic tether offers a vast and very rich opportunity for scientific investigation. This section does not attempt to list all possible experiments--but, rather, to provide a few examples in several of the more obvious areas of study.

1. Generation and Propagation of Waves in Plasmas

A large number of wave modes can be excited and studied, ranging from ULF/ELF, which may be useful for communications, to various plasma and hydromagnetic modes, which are of scientific interest because of their frequent occurrence in solar system plasma physics and of techno-

logical interest because of their impact on tether power/thrust generation. For example, Alfven waves will serve to disperse the space charge deposits at the tether ends, thereby creating a better contact with the ionospheric plasma, while high frequency plasma waves may heat the plasma and produce power losses.

2. Field Aligned (Birkeland) Currents

Once the electromagnetic tether has a deposited charge of opposite sign at its ends, the regions of charge must recombine. It is thought that this will occur via currents traveling along the geomagnetic lines of force down into the E-regions of the ionosphere where collisions with neutrals allow migration across the field lines to close the circuit.

This process is of scientific interest because of the importance of Birkeland current systems in the earth's auroral zone, in the sun, and in various planetary systems, such as Jupiter and Saturn. Such current systems may also generate instabilities, radiate certain hydromagnetic wave modes, and create double layers—all of which are frequently encountered in nature.

3. Large Body Plasma Interactions (Sheaths and Wakes)

The plasma flow interaction with large bodies in space is of both scientific and technological interest. It is a necessary part of understanding the environment of any large structure in space, such as a space station or space platform, and it is (as it occurs for artificial bodies orbiting within the ionosphere) qualitatively similar to certain interactions of space plasmas with natural bodies in the solar system. Such interaction, in fact, are extremely common in nature since plasma exist throughout the observed universe and they flow past various types of obstacles. Therefore, such patterns occur in earth orbit, in solar system plasma physics, and in astrophysics.

The investigation of certain examples of flow interactions (large conducting/nonconducting bodies, magnetic bodies, etc. in a supersonic-subAlfvenic flow) can be carried out in earth orbit with

tethered test bodies and diagnostic instruments mounted on booms, on tethered instrument packages, and on free flyers.

4. Process Simulation

Process simulation is the investigation of certain physical mechanisms or processes, which occur in natural phenomena. It makes use of the concept of qualitative scaling which requires only that scaled quantities which are much greater than unity in space remain so in the scaled experiment--but not necessarily to the same order of magnitude (i.e., $P_{Space} \gg 1$ then $P_{Exp} \gg 1$). Likewise, the inequality must be preserved for quantities which are much less than unity (i.e., $P_{Space} \ll 1$ then $P_{Exp} \ll 1$). Only when quantities are on the order of unity, they must be closely scaled (i.e., $P_{Space} \sim P_{Exp}$).

The range of plasma and electromagnetic processes which occur both in the solar system and in earth orbit is surprisingly large, as shown in Table 1.

TABLE 1

PLASMA PHENOMENA

Rarefaction Wave	Local Acceleration
Shock	Runaway Electrons
Plasma Void	Plasma Waves/Instabilities
Converging Streams	Turbulence
Field Aligned Currents	Mass Addition
Current Sheets	Beam-Beam Interactions
Sheaths	Boundary Layers

The study of such processes in earth orbit will increase our understanding of their behavior. This understanding can be extrapolated to explain measurements made during planetary missions much the way our understanding of the Earth's magnetosphere was used to enhance our understanding of planetary magnetospheres.

III. CONCERNS

The panel identified eleven specific concerns in the potential application of the electrodynamic tether. A primary concern is the development of a coupling mechanism between the tether ends and the surrounding medium; particularly in the very high current applications recommended herein for power and thrust generation. Tether materials and high voltage technology also require specific attention. The eleven concerns are as follows:

- Tether materials (strength, conductivity, insulation, etc.)
- High voltage technology
- Spacecraft charging
- Variations in power with tether angle and magnetic field variations
- Impedance of collection mechanism and return circuit
- Radiation losses along the line
- Collection body properties (e.g., effect of size on radiation and alternate collectors)
- Coupling with ionosphere; plasma drag and wake
- Emitter properties; impedance, particularly with respect to high current handling capability
- $\vec{I} \times \vec{B}$ force effect on tether angle and possibly orbit characteristics
- Detectability of radiation on Earth

IV. RECOMMENDATIONS

The electrodynamics panel recommends that the specific research activities listed below be undertaken in the near term.

- Proof-of-concept flight experiment to investigate plasma contacting devices
- Further development of the theory for:
  - Formation and characteristics of Alfven wings
  - Radiation of higher frequency modes

- ULF/ELF radiation and propagation through the ionosphere to ground

- Free flyer (with plasma and wave diagnostics) to measure wave emissions and plasma parameters in the near field of the tether/satellite

- Ground based measurements of ULF/ELF emissions

- Laboratory investigation of:
  - Plasma wakes, electrodynamic drag and the effect of potentials
  - Optimization and current capacity of charge emission and plasma bridge devices.

TRANSPORTATION

I. INTRODUCTION

The panel covered eleven tether applications for space transportation (Table 2). The first seven involve the transfer of momentum between two masses at the tether tips, and the remaining four use tethers for controlled interaction with the environment.

TABLE 2

TRANSPORTATION APPLICATIONS OF TETHERS

	MOMENTUM TRANSFER TETHER APPLICATIONS Operation	Deployer On:	ESTIMATED PRACTICALITY
1	Payload Boost	Orbiter	High
2	Upper Stage Boost	Orbiter	High
3	E.T. Deboost	Orbiter	Medium
4	Shuttle Deboost	Space Station	High
5	Shuttle Docking	Space Station	Medium
6	Payload & OTV Boost	Space Station	Medium
7	Payload Boost	Upper Stage	Medium
	ENVIRONMENTAL INTERACTION TETHERS		
8	Lunar Assist & Eccentricity Change		?
9	Aero-Maneuvering by Remote "Sail" or "Kite"		High
10	Electrodynamic Deceleration		?
11	Lunar & Planetary Applications		?

Momentum transfer tethers typically provide considerably lower Delta-Vs than rockets, but they can use as a reaction mass objects that have already served other functions and may later be of use in other ways (e.g., orbiters).

Tethers are most clearly useful where opposite momentum changes are desired at the two tip masses, but they can also pay for themselves by eliminating a need for rocket guidance systems, or by allowing space-

station-based high I_{sp} thrusters to displace lower I_{sp} propellant use by free flyers.

Tether stresses scale with tether length, so halving the required Delta-V allows for a fixed tether mass to handle four times as much payload. As a result, for small enough in-plane orbital transfers (under about 300-600 fps), tethers require a less dedicated mass than rockets and can thus pay for themselves in one use.

II. APPLICATIONS

1. Shuttle Dlivery of Payloads to Higher LEO Orbits

This concept involves deploying a payload upwards from a shuttle and releasing it near the apogee of an eccentric shuttle orbit. Assuming that the payload/orbiter mass ratio is 1:6, this operation raises the payload apogee by 6/7 of the tether lenegth, and the payload perigee by 6-12 times the tether length, depending on whether the tether is hanging or swinging. The orbiter's apogee and perigee both shift downward, by 1/7 and 1 to 2 tether lengths.

Such tether operations allow delivery of large payloads to higher orbits than otherwise possible even with OMS kits. The required tether deployer should be more compact than OMS kits, and should allow roughly twice as much gain in service altitude for a given reduction in payload. This is because standard STS operations involve an apogee boost, perigee boost, and perigee deboost, all of which increase mile-for-mile with service altitude. Tether operations require radically smaller perigee boosts and deboosts which increase only slowly with service altitude, plus a tether mass that increases with the square of the difference between the service altitude and 100 nm.

2. Shuttle-Based Tether for Deploying Upper Stages

This application is very similar to Application 1. The main difference is that the payload/rocket combination is best released when the orbiter is near perigee, to minimize the "gravity losses" associated with the upper stage burn. Savings may generally be much smaller than

with Application 1 because here the tether just shrinks the required upper stage rather than eliminating the need for one.

The exact level of benefits provided by the tether depends on many details of the mission that will merely be mentioned here. First, the orbiter apogee before the operation may or may not be required by other payloads, and the apogee drop caused by the tether may or may not require makeup. If the upper stage comes in a fixed size that is slightly too small, or if the payload plus required stage weight exceeds the structural limits of the orbiter, a tether operation or some other performance-enhancement may be required.

3. Downward Release of External Tank from Shuttle Orbit

This application is an "upside down" version of Application 1, using the External Tank (ET) as "payload." The major effects are to initiate a controlled reentry of the ET and to boost the orbiter perigee; both of these effects are beneficial.

The ET is currently disposed of while the orbiter is on its way to orbit. This constrains the orbiter to launch trajectories from which suitable disposal sites can be reached during the first orbit. In particular, current operations preclude service to inclinations between 57° and 70° from either KSC or VAFB, due to lack of suitable ET disposal sites.

Taking the ET into orbit before disposing of it allows the shuttle to wait until the earth rotates underneath the orbital track and provides a safe disposal site. For some cases already investigated, there are apparently many suitable opportunities during each day.

4. Space Station Altitude Reboost and Shuttle Deboost with Tether

This is the first of three tether applications that use a space station-based tether deployer. Space station basing relaxes constraints on retrieval time. It also allows more ambitious tether facilities since the tether system need only be launched once, rather than every mission it is to be used.

The application considered here reduces the drag-makeup requirements of a space station by "scavenging" momentum from an orbiter that is about to leave the station to reenter. An early version might attach the tether to a bridge in the payload bay, and use a tether long enough to drop the orbiter perigee to about 100 nm. This leaves the orbiter in orbit after release, in case the initial attempts to close the payload doors are unsuccessful.

Releasing a 180,000 lb orbiter into a 200 x 100 nm orbit from a station at 215 nm provides enough momentum to displace space station makeup burns of about 4200 lbs of Orbital Maneuvering System (OMS) propellants (or 2900 lbs of cryos) on each mission. It also reduces orbiter deboost OMS-use by about 3700 lbs, but that must be kept available as an OMS reserve, to deboost the orbiter in case the tether breaks.

5. Shuttle Docking with Space Station Via Tether

This operation is in essence a "time-reversal" of Application 4; i.e., the orbiter docks with a tether deployed down from a space station and "borrows" momentum from the station during the mission. Major propellant savings only occur if the station has excess momentum from energetic tethered-deboosts of orbiters and ETs, or uses electrodynamic tethers or other electric thrusters.

In this case, the savings scale with tether length are about 350 lbs per nautical mile (nm) of tether for hanging-capture operations and up to 620 lbs per nm for swinging captures. If the ET is to be brought to the station for propellant scavenging or other use, the savings are about 30% larger.

6. Tethered Boosting of Payloads from Space Station, With High I_{sp} Makeup

This application is a space station-based version of Application 2. If lost momentum is made up conventionally, the benefits are limited, but--as in Application 5--radical payload increases are possible if high I_{sp} thrusters are used.

The net effect of tethered boost and low thrust, high I_{sp} makeup of lost momentum is to combine the low overhead mass and transfer times characteristic of chemical rockets, with the low propellant consumption of high I_{sp} thrusters. This "best of both" combination provides an ideal application for electric thrust devices.

There are several unobvious benefits as well. First, the electric power system remains safely below the damaging Van Allen belts. Second, "off-peak power" can be used to reboost the station; this smooths power demands on the space station and reduces storage requirements. Third, the electrical power system and the thrust device are always accessible for maintenance and repair, since they are kept on the space station itself. And fourth, magnetic field strengths and electron densities are greater in low earth orbit (LEO) than at higher altitudes, so space station-based electrodynamic tethers may be practical for momentum makeup. This might totally eliminate any need for momentum makeup propellants.

7. Using Tethers to Boost Payloads and Deboost Spent Rocket Stages

This is the only tethered momentum transfer application discussed which is based neither on the shuttle nor on a space station. It is based instead on upper stage vehicles. The purpose is to transfer some of the momentum invested in a spent stage to its payload. Since this is done only once for each boost operation, the tether must fully "pay its way" each time it is used. Hence, this operation is limited to relatively modest Delta-Vs (on the order of 300 ft/sec). This in turn should allow payload increases of a few percent.

If the stage is expendable, then the tether pays for itself primarily by boosting the payload, and only to a minimal extent by causing a prompt reentry of the spent stage. If the stage is reusable, tethered deboost may have significant value, since it can reduce the propellant required to return the stage to the space station that services it. Deploying a tether may itself be valuable, if the tether has an aeromaneuvering device at its end, or is a bare conductor that can create enough electrodynamic drag to complete the deboost.

8. Modification of Orbital Energy and Eccentricity by Control of Tether Length

In the inhomogeneous gravity field, the net gravity force on the extended body does not coincide with the gravity force that would act on the total force at its center of mass, but depends on the configuration. Thus, if internal mechanical energy is used (or absorbed) to force appropriate modifications of this configuration, the net force will change, and the motion of the center of mass can be affected without mass expulsion. The net torque about the earth's center remains zero, however, so no effect on the overall angular momentum will occur.

This effect could probably be most useful in circularizing highly elliptic orbits by absorption of mechanical energy (but without propellant expulsion), or vice versa, to achieve near-escape from moderately high initially circular orbits, this time by expenditure of energy on board. It is probably premature to think of applications, however, until the fundamentals of the effect have been more thoroughly studied (i.e., are there more convenient, high amplitude, lower frequency "pumping" laws?). It is interesting, however, that there is the actual possibility of using purely internal forces for orbit modification.

9. The Satellite Sail

An aerodynamic surface is lowered from a satellite on a long tether into the upper atmosphere, where it is oriented to give a horizontal force on the satellite through the tether. This force is modulated as a function of the orbital position in order to precess the orbit or to change its orbital plane.

The satellite sail could change the orbital plane of the space shuttle by 0.5-1.5 degrees per day with a 100-square meter airfoil lowered to 90 km altitude. The losses associated with the drag of the tether and the airfoil are much less than the corresponding losses due to changing the orbital plane by direct rocket thrust or by dipping the shuttle into the upper atmosphere and performing an aerodynamic maneuver. The sail would allow the shuttle to deploy a satellite into one orbital inclination, change its orbit, then deploy or retrieve a satellite in a second

orbital inclination before returning to base. Alternately, the sail could be deployed on the satellite itself, allowing it to change its plane from the nominal 28.5° orbit of the shuttle to its desired orbital plane. This could be done at leisure, taking days or weeks and requiring very little energy. This technique would free the shuttle, with its greater mass, from having to change its plane.

10. Electrodynamic Braking of Tethered Satellites

To make continued close observations by explanatory probe, the probes should be captured in a low altitude orbit. For planets with an ionosphere and magnetosphere, electrodynamic braking can provide a soft deceleration mechanism for capture, which would eliminate the need for retro-rocket propulsion. For satellites in earth orbit, the same electrodynamic braking could be used to deorbit.

The satellite is divided into two approximately equal parts by payout of an electrodynamic tether in a gravity gradient stabilized configuration. A retarding force is exerted on the tether due to the induced current. The power in the current generated in the tether is dissipated in the tether itself or in an auxilliary load, where it is radiated away. As a result, the orbital velocity is reduced.

11. Planetary Tethers

A long tether is lowered from a satellite in orbit about the moon, for example, and tethers the satellite just beyond the Lagrangian unstable balance point L1 or L2. The satellite is then raised somewhat to just beyond the balance point and then moves on the tether like a spherical pendulum. Because of the lower gravitational field of the moon compared with the earth, such tethers could be done with existing high strength materials.

The lunar tether could anchor a satellite just beyond L2 on the far side of the moon, 70,000 km from the lunar surface. From this vantage point, oscillating in a wide orbit that is a complicated Lissajous pattern behind the moon, it would be visible from the earth and the far side of the moon simultaneously, and be able to provide continuous communication

with any probe or installation on the far side of the moon. The lunar tether could also be emplaced on the near side of the moon, anchoring a mass past the L1 point, 66,000 km from the moon's surface. This installation could be used to bring up materials from the surface of the moon by simple mechanical means on the supporting tether. The energy requirement for this is just 0.7 kW-hr per kilogram. Once the material is brought past the L1 point, it can be released into a high earth orbit, where it could be used for construction of solar power satellites or could be used for the production of liquid oxygen rocket propellant for use in earth orbit. The installation on the near side of the moon could also be used to provide a means for soft lunar landings without the use of retrorockets by allowing payloads to move down the tether in a controlled fashion.

III. CONCERNS

The concerns of the panel are as follows:

STATUS:

- There are no unique technological concerns beyond materials and dynamics
- Transportation applications can be achieved early—the present tethered satellite deployer can reboost/boost existing satellites in LEO

ISSUES:

- Development of Uprated Tether Hardware
  - Improved payload capability
- Passive Deployment/Retrieval Technology
  - Reduces hardware costs
- Customer/User Acceptance
  - How is confidence in the use of tethers developed?

IV. RECOMMENDATIONS

Applications 1 through 7 Table 1 (shuttle, external tank, and space station tethers) should be thoroughly studied as soon as possible to:

- **Define the systems accurately enough to permit valid engineering and cost comparisons.**
- **Identify technological implications and any new technological developments required.**

Application 8 (angular momentum pumping) should be investigated conceptually.

Applications 9 and 10 (aerodynamic sails and electrodynamic braking) represent tether interactions with the environment. Both have high promise and technological studies should be pursued.

Application 11 has not received much attention. Tethers may have utility in further planetary or lunar exploration. Planetary study groups should be encouraged to include studies of tethers in their future activities.

ARTIFICIAL GRAVITY

I. INTRODUCTION

The panel emphasized the relationship between tethers and the space station. Tethers can be embodied into NASA's future space station development both as an experimental facility and as a technology for systems enhancement (including attitude control, power source, station-keeping, friction induction and traction provisions, docking, deployment, etc.).

Early action should be taken to ensure that the basic tether system is baselined into the initial space station architecture and that further concept studies be arranged to embody this basic capability. In the short term, 1991 through 1995, the application of tether techniques could be similar to those employed on intervening space shuttle missions. Space station tethered satellite operations could be continuous, subject to need and occasional association with local spacecraft operations in the proximity of the space station. The use of the tether principles could be further explored for attitude control and/or attitude stabilization damping, proximity operations, etc.

For new tether uses, action should be taken to look at the tether for holding storage uses, proximity operations, and for extension of the capabilities of attached payloads systems. These applications should emphasize dynamic off-vertical tethers; rapid deployment, active-steered tethers; tether-boom combinations; and other concepts.

II. APPLICATIONS

The Artificial Gravity Panel first considered possible general requirements and applications for artificial gravity under a wide range of circumstances (see Table 3). The panel than explored appropriate means of filling these requirements (see Table 4). The focus was on using tethers because of the Applications of Tethers theme of the workshop. The orbiter itself does not appear to be a good platform for tether R&D work because of operational time limits on the orbiter. Therefore, the panel deliberations concentrated on tethers that would be attached to space stations.

However, orbiter demonstrations and external tank demonstrations might be useful in exploring and developing tether operations prior to the space station.

TABLE 3

TETHERED SATELLITES GRAVITY UTILIZATION CATEGORIES AND APPLICATIONS

CATEGORY	EXAMPLES
SCIENCE	ANIMAL/PLANT GROWTH, CRYSTAL GROWTH, FLUID SCIENCE, SIMULATIONS IN CHEMISTRY/PHYSICS
TECHNOLOGY	FLUID STORAGE, ATTITUDE CONTROL SIMPLIFICATION, OTHER SUBSYSTEM ENHANCEMENTS
MEDICAL	STUDY/REDUCE EFFECTS OF ZERO-G ON HUMANS. INVESTIGATE MEDICAL PRODUCTS/SERVICES IN LOW G
HABITABILITY	IMPROVE MAN'S PRODUCTIVITY AND COMFORT BY PROVIDING SOME LEVEL OF GRAVITY
OPERATIONS	ORBITAL REFUELING, INSTRUMENT/ANTENNA FARMS, TETHERED TMS FOR SPACECRAFT RETRIEVAL

TABLE 4

ARTIFICIAL GRAVITY MEANS

Means:

- **Science: Variable Gravity Facility ($<10^{-3}$)**
- **Technology: Manned R&D Facility**
- **Medical: Variable Gravity Facility ($>10^{-3}$)**
- **Habitability: Rotating System (>0.10 G)**
- **Operations: Tank Farm**
  Antenna/Sensor Farm
  TMS/OTV Retrieval

Each of the Artificial Gravity Means are described below. Each utilizes tethers to provide controllable unidirectional levels of acceleration over long periods of time. Availability of relatively large dedicated volumes equipped with adequate controls (from in-space or earth personnel) are assumed. Careful attention must be given to stability of the various configurations against random or oscillatory motions of the overall tethered systems over relatively long periods of time (minutes to months).

A. Microgravity Sciences

Tether systems provide new types of microgravity (MG) environments that can be used to meet a large variety of user's needs in the fields of life sciences, material sciences, and fluid sciences.

Typical examples in the different fields are:

- Life sciences (determination of threshold g-values for biological processes)
- Material sciences (determination of the level-frequency acceptability regions for crystal growth processes)
- Fluid sciences (g-jitters, contact angle hysteresis, dynamic wetting, spreading, influence of g-history on critical point phenomena, stability enhancing by means of time variation of g-levels)
- Processes (optimization by means of so called g-tuning).

B. Technology

A tether system for storing and transferring liquid must primarily position and maintain fluid over the tank outlet. This should also provide for easier quantity gaging. The tether should provide separation of the tank farm from the space station to provide hazard clearance from explosion and contamination. The tether should provide separation of the OTV docking from the space station to prevent accidental collision with manned systems.

C. Medical

Artificial gravity can be used to reduce/eliminate the deleterious effects of the zero-g environment on humans. The principal organ systems known to be clearly affects by the loss of a 1-g bias are the

cardiovascular, vestibular, and skeletal. The objective is to create an environment or habitat at a g-level appropriate to diminish these.

The ability to achieve these accelerations while limiting both coriolis and gravity gradient (GG) effects will probably require rotating tether systems due to present technology limitations which cause tether weights to become excessive in GG forces of this magnitude.

D. Habitability/Productivity

Because of man's evolution in a 1-g environment and man's extensive knowledge of 1-g environmental design, he has not yet mastered the zero-g environment as well as may be possible. There may be many ways to improve man's productivity and general comfort (habitability) with zero-g. Further study is clearly needed to justify any tether applications in this field.

E. Operations

Large multifunctional orbiting facilities such as space stations and space platforms impose new operational requirements. Such facilities will be composed of various functional elements. These may include, for example, transfer vehicle docking and maintenance equipment, laboratories, and sensor packages. Potential benefits are anticipated from the separation of some of these elements from the main structure. The major benefit is isolation from contamination or interference by other elements.

III. CONCERNS

The concerns of the panel are listed below:

- Fluid Storage and Transfer
  - Tank development from shuttle or space station
  - Development of reliable docking and transfer mechanisms
  - Proper planning for malfunction and contingency situations
- Free Flyer Tethered Systems
  - Safe deployment
  - Method of orbit correction in tethered configuration
  - Dynamics analysis

- Microgravity Materials Processing
  - Achieving and maintaining desired microgravity characteristics
  - Dynamics analysis if tether ad rotation are combined
- Large Scale Tether Operations
  - Methods of construction and deployment
  - Collision hazards with free flying spacecraft
  - Orbit maintenance
- Manned Artificial Gravity Laboratory

  (Similar to Large Scale Tether Operations)

IV. RECOMMENDATIONS

Not envisaged for the initial space station, but not precluded as a sponsored investigation is the need to investigate artificial "g" as a requirement for continuous manned habitation of the space station. Sensible "g" levels would require tethered displacement of large elements of the space station configuration.

For long term space station evolutionary development, the consideration of more complex tethering concepts (constellations, launches, etc.) should be investigated including large scale utilization of tethered systems (tank deorbiting, on-orbit uses of external tanks, etc.).

The panel's recommendations for space station tethered applications for the near term include experiments both from a station and a platform at a distance, and a tethered supported operation like stowage—perhaps a tank farm. Tethered grappling devices might be of interest sooner. Mid-term space operations might be expedited for tank farms, antenna farms, and tethered retrieval of objects. Over the long term, gravity gradient and rotation-induced g levels might be increased from 0.01 g to a few times 0.1 g.

The aforementioned recommendations are summarized in Table 5.

TABLE 5

ARTIFICIAL GRAVITY PANEL RECOMMENDATIONS

- SPACE SHUTTLE TETHERED APPLICATIONS (1984-1991)
  - Preliminary, Short Term (Days), Investigations
    - Concept Verification
    - Preliminary System Design Qualification
- SPACE STATION TETHERED APPLICATIONS
  - Near Term (1991-1995)
    - Experiments from Station
    - Experiments from Platform
    - Tether Support Operations
      - Stowage
      - Proximity Operations
  - Mid Term
    - Systems Contributions to Station
      - Tank Farm
      - Antenna Farm
      - Tethered Retrieval
  - Long Term
    - Artificial "g" as a Station Characteristic
    - Large Scale Tether Operations

CONSTELLATIONS

I. INTRODUCTION

Figure 1 provided a starting point for the definition of "Constellations." This definition was provided by the NASA Applications of Tethers in Space Working Group. The panel used this definition as a starting point.

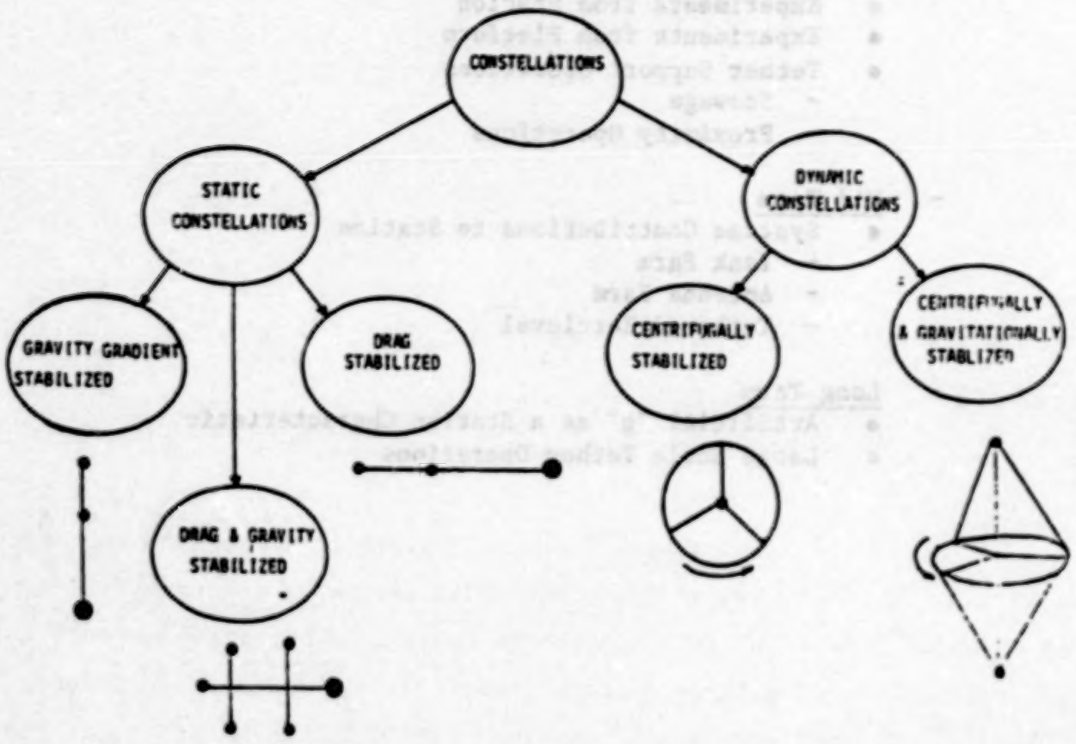
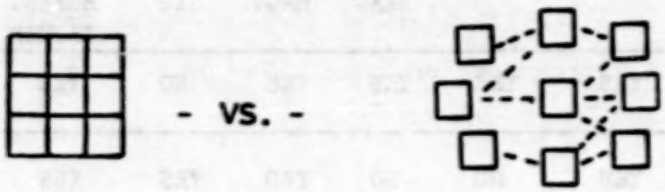


Figure 1. Tethered Constellations

Based on discussions during the Workshop, it was concluded that combined centrifugal/gravity stabilization would be extremely complex to implement. Therefore, unless an overpowering need for this concept is developed, it should not be pursued. If it must be pursued, it can probably be done with some limitations. In addition, constellations that include both tethers and fixed or rigid members should be included.

The purpose of a constellation is to provide basic architecture that allows space activity to be "concentrated", and at the same time "distributed", by tying all the elements together (Fig. 2).



CONCENTRATED - VS. - DISTRIBUTED

- ENVIRONMENT
- UTILITIES
- LOGISTICS
- SAFETY
- GROWTH/FLEXIBILITY

Figure 2. Purpose of Constellation

By their very nature, some space activities gravitate towards a constellation architecture. One of the most desirable characteristics of this mode is "isolation" for laboratory, contamination, gravitational and other adaptations of a large space platform. A near zero-g environment can also be attained and varying degrees of gravity can be achieved. So, there are many desirable spin-offs from a distributed system, from the standpoints of utilities, logistics, safety, and growth/flexibility.

II. APPLICATIONS

Starting from the definitions of the introduction, the panel attempted to quantify—put a set of first order limitations on—each category of constellations (see Table 6). For the present, the panel suggests dropping the combined gravity gradient plus dynamic stability out of the picture. Applications have been assessed relative to low earth orbit (LEO), geosynchronous earth orbit (GEO), and into one-, two- and three-dimensional constellations.

TABLE 6

CONSTELLATIONS STABILIZATION FEASIBILITY

STAB / ORBIT	GRAV GRAD	DRAG	GRAV GRAD + DRAG	GRAV GRAD + MAG.	GRAV GRAD + J22	GRAV GRAD + MOMEN. TETHER	DYNAMIC (SPIN)	DYNAMIC + GRAV GRAD
LEO	YES	YES	YES	YES	NO	YES	YES	NO
GEO	YES	NO	NO	TBD	YES	YES	YES	NO
CONSTELLATIONS DIMENSIONS	1	1	1-2	2	2	2-3	2-3	3

To apply gravity gradient harmonics at LEO, one must think in terms of a tether with a pumping action—like a swing. If the pumping takes place at the proper point of the arc, positive results can be achieved. With the aid of a tether and pumping operation (e.g., similar to running masses up and down a rope), there are some momentum exchange devices that take advantage of gravity gradient anomalies, e.g., J22. Some very attractive momentum exchange characteristics result from the use of pumping actions with the tethered concept.

The constellation panel believes that tethered constellations will provide the capabilities listed in Table 7.

TABLE 7

TETHERED CONSTELLATION CAPABILITIES

Capabilities:

- Allows Unpowered Formation Flight of Spacecraft or Payloads
- Allows Environmental Gradient Measurements
- Provides an Environment Free of Particle and Molecular Contamination
- Provides an Environment Free of Dynamic Perturbations
- Provides for Greatly Simplified Orbital Servicing of Multiple Spacecraft/Payloads
- Rotational Tethered Constellations Provide Constant Attitude Control

III. CONCERNS

In its discussions, the panel expressed concern over the unresolved critical issues identified in Table 8.

TABLE 8

TETHERED CONSTELLATION CRITICAL ISSUES

Critical Issues:

- Configuration Stability
- Simulation Models and Control Laws
- Unknown Elements of Drag Stability
- Deployment Procedures
- Mass Exchange, Attachment, and Mass Movements Along Tethers

IV. RECOMMENDATIONS

The initial step in establishing the feasiblity of tethered constellations would be to conduct experiments from the shuttle possibly using the Tethered Satellite System (TSS) hardware currently under development as shown in the left of Fig. 3. The next step would be to utilize a mass (such as a Spacelab pallet) or an intermediate mass that can be attached and moved along a gravity gradient stabilized tether. Variations in microgravity could be studied as well as obtaining useful information on moving tethered masses in space.

A "long term" tethered constellation experiment could be left in orbit as a free flyer and be revisited or recovered by the orbiter as shown in the right of Fig. 3.

The above experiment should be investigated from every possible angle included: one or two days orbit flight; the long-term dynamics associated with noncircular orbits; masses that can "reel" up and down a tether; masses that migrate up and down a tether; and changing tether lengths, as well as free flying experimental tethered masses that can be serviced and recovered by the orbiter.

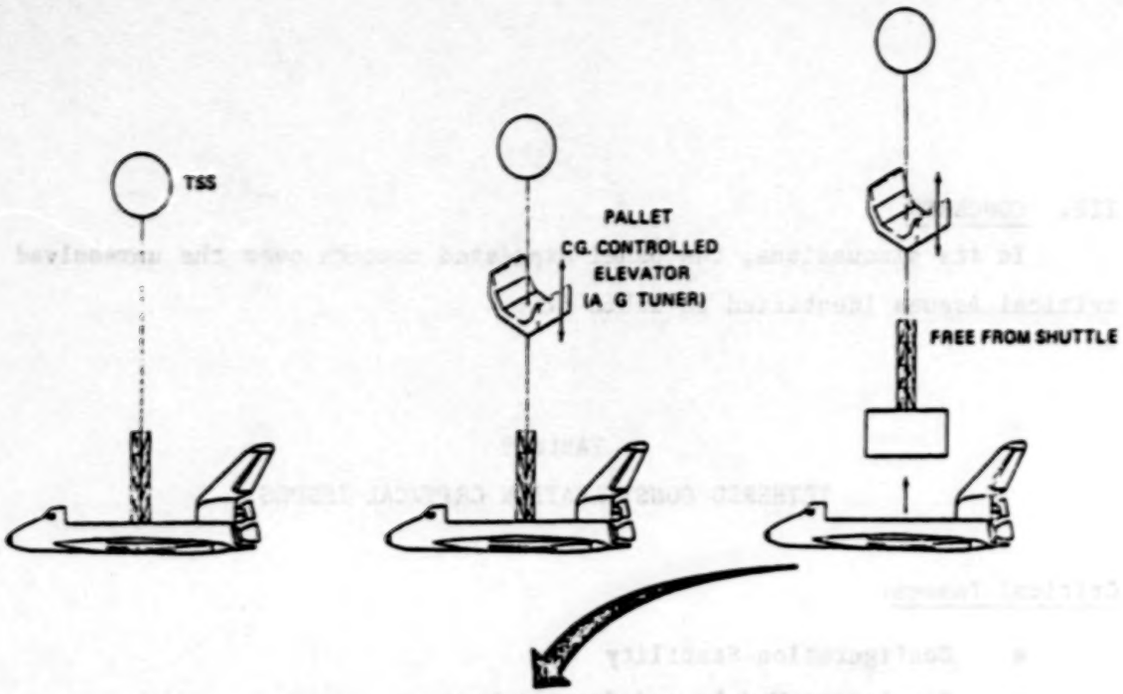


Figure 3. 1st Step Toward Constellation

Additional work needs to be done in a drag stabilization mode. The panel believes the characteristics are, in fact, achievable but more control laws and stability work needs to be done in a drag free mode. An early drag type experiment needs to be done. To illustrate, a mass that has a low drag character could be tethered to a high drag mass such as the shuttle. To better understand the drag stabilized mode, the mass could be moved back and forth (see Fig. 4).

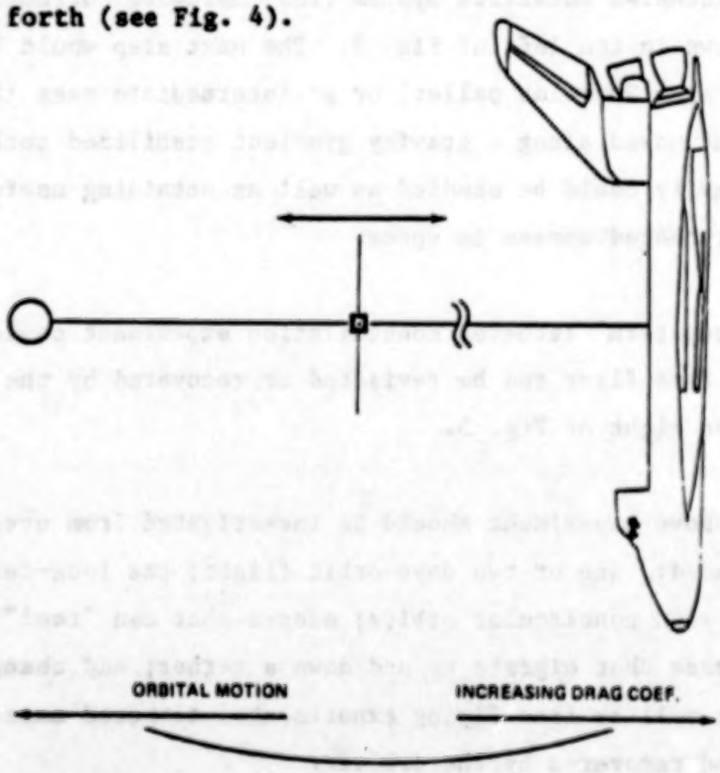


Figure 4. Drag Stabilized Constellation

Finally, some early demonstrations need to be done on a rotational stability. A centrifugally stabilized demonstration could be done (Fig. 5). The only thing that has been addressed thus far is what are those characteristics and phenomena and losses which need to be understood, and which can be put on the technological shelf for a later application. In each of these earlier demonstrations, such as a rotation stabilized system, one could, in fact, do science along with the technology demonstration of constellation type of tethered systems.

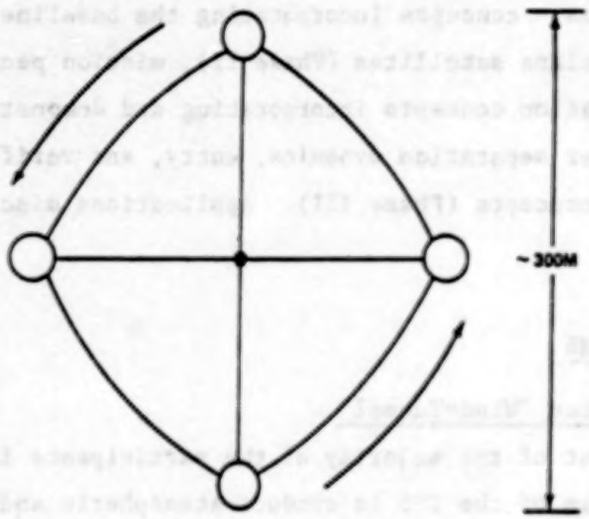


Figure 5. Rotation-Stabilized Constellation

Table 9 summarizes early constellation studies and experiments.

TABLE 9

EARLY CONSTELLATION STUDIES AND EXPERIMENTS

- Update Dynamic Models and Control Laws for Nearly Equal Masses
- Mass Attachment and Motion Along Gravity-Gradient Stabilized Tether
- Numerical Study and Analysis on Drag Stabilization and Its Role in Constellations
- Drag Stabilized Constellation Demonstration
- Rotation-Stabilized Constellation Demonstration

TECHNOLOGY AND TEST

I. INTRODUCTION

The tasks undertaken by the Technology and Test panel were threefold: (1) review the state of technology relative to the Tethered Satellite System (TSS), (2) define the technology areas which could benefit from the TSS, and (3) define the technology and test support required by other TSS applications.

Many concepts were presented and discussed--each deserving of additional studies-- concepts incorporating the baseline satellite (Phase I), modified baseline satellites (Phase II), mission peculiar configurations and combination concepts incorporating and demonstrating tether operations, tether separation dynamics, entry, and verification of deboost/reboost concepts (Phase III). Applications discussed by the panel are shown below.

II. APPLICATIONS

A. Tethered "Wind-Tunnel"

The interest of the majority of the participants in the panel was related to the use of the TSS to conduct atmospheric and aerothermodynamics related research. The TSS can provide access to that part of the atmosphere which is presently probed only briefly by rockets and reentry vehicles. The use of the TSS as a "wind-tunnel" would provide the capability to define the upper atmosphere and its variations as well as provide data relative to rarefied gas dynamics (free molecule, slip and transition flows) required in the design of advanced STS, aerobraking and aero-assisted vehicles. Such a system could provide the pressure, loads and heating data required which is not presently available from ground facilities.

B. Large Aperture Antenna Range

A tethered probe could be used to calibrate and perform measurements on large aperture structures and antennas. Studies have indicated that the use of a tether system for Large Aperture Antenna calibration was not competitive with using the TDRSS.

C. Vehicle Attitude Control

The tether tension that exists between two bodies in a stable gravity gradient orientation can be used for the independent orientation of each body in pitch and roll. This could be demonstrated using the TSS with either an articulated mast or the RMS with a special end effector. A successful demonstration using the TSS would allow this concept to be considered for the Space Station. The Station could be allowed to grow to very large proportions and still be precisely controlled. The loading in the tethers could be kept low so that tether mass including a large strength safety factor would not be a constraint.

D. Orbital Wake Effects

A large body (Shuttle, space station, large structures, etc.) moving in LEO sweeps up the tenuous medium consisting of residual neutral gas and ionospheric ions to produce a void in its wake. The void is eventually filled with diffusing neutrals and ions and its length is determined by their temperature. A smaller object co-orbiting with the large body and positioned in its wake would not be exposed to the ionospheric plasma.

An experiment was recommended to the panel to study the electrical properties of the orbiter wake region, the objective of which is to determine what plasma effects do actually occur in this region, and how significant they might be relative to EVA or satellite deployment in the orbiter wake when the vehicle is in polar or near-polar orbits.

E. Space Power Technology

The results of ongoing work related to space power (solar arrays) indicated that there is a serious problem relative to high voltage connections with the orbiter. A multiple short tether concept that could provide advantages over a long single tether was discussed. Multiple short tethers could reduce input voltages, lessening requirements for insulation and possibly reducing connection problems.

F. Space Station Modules

A suggestion that was discussed by the panel was the possible development of a tethered subsystem that could be deployed from a space station as an emergency habitat. If an emergency would occur on the space station, the subsatellite could be used as a temporary habitation; and, if necessary, could be used to return to the earth. The subsatellite concept could also be used to store dangerous or toxic material as well as fuels and pyrotechnics devices.

G. Utilization of Gemini Deployment and Stationkeeping Techniques

The Gemini II flight demonstrated a rotating configuration in which the Gemini spacecraft was tethered to an Agena rocket. Centrifugal force maintained tension in the tether following spin-up of the configuration. The Gemini XII flight demonstrated a gravity gradient stabilized configuration. The panel discussed the possibility of utilizing the Gemini deployment and stationkeeping techniques and applying them to the External Tank tethered to the orbiter in a rotating configuration. Artificial gravity (0.001 to 0.1 g) could be generated in the Spacelab/Orbiter.

III. CONCERNS

During the workshop, two technology issues dominated the deliberation in the panel. These issues were tether materials and dynamic modeling technology. The former, tether materials, was by far the dominant concern of the panel. It was also of significant concern to the Transportation and Electrodynamics panels. Although it was agreed that the immediate problem associated with tethers for the 20 km electrodynamic and 100 km atmospheric missions can be solved--engineering design fixes--it is recommended that an extensive materials development program be initiated to develop the tethers required to support the future applications being defined.

To support TSS design studies, it is necessary to develop tether dynamic model computer codes for definition of mission and tether requirements. Present major codes are very elaborate, expensive to run, and not very user friendly--this technology concern is being addressed by the TSS flight project.

The recommendations from the TSS project which should be available for review in 1984 should be quickly evaluated and implemented to support program development and tether applications feasibility studies which will be key elements in the definition of future technology development programs.

An additional technology concern was related to the manufacturing of tethers. The development of complex tethers (nonconducting; taper/double taper; long >100 km; conducting - embedded conductors; fiber optics; superconductors; etc.) and their application to space stations requires investment in new manufacturing capabilities for both Earth based as well as space-based systems.

Tables 10 through 13 summarize key issues in: Dynamics, Guidance and Control; Material Degradation; Satellite Tracking; and Remote TSS Operations.

TABLE 10

DYNAMICS AND GUIDANCE AND CONTROL

- There are today a large number of orbital mechanics models, all differing in some respects: rigid tethers, inextensible tethers, drag, distributions of the mass of the tether and of the satellite, etc.
- What is needed, and is being developed, is an engineering dynamics model. Such a model will be sufficiently accurate for many purposes, e.g., mission timelines.
- Such a model will also be used extensively for the development of "standard" control algorithms.

TABLE 11

MATERIAL DEGRADATION DUE TO ATOMIC OXYGEN

- Three Kevlar samples were flown on the STS-5, each maintained at a different temperature.
- The three samples were not under tight control, e.g., no clean room procedure, handled by various people, etc. The reason for this was "very little time available."

TABLE 11 (CONT.)

MATERIAL DEGRADATION DUE TO ATOMIC OXYGEN

- The three samples were subjected to break strength tests, and compared to five samples (from the same lot number) which weren't flown.
- Using non-parametric tests, there is about one chance in sixty that the lower breaking strength of the three samples flown was a random fluctuation. Therefore, it was concluded that the strength of the flown samples had decreased.
- At the present time it is not known what caused this decrease. Scanning electron microscope photographs show that the exposed Kevlar surfaces have an eroded appearance. Blame has been placed on atomic oxygen.
- There are several samples of different materials, Kevlar included, both bare and coated, which will be flown on STS-8.
- Even if Kevlar 29 is degraded, its diameter can be increased so that adequate strength with a generous margin of safety for a 36 hour mission can be achieved.
- MSFC and Martin Marietta are presently conducting an exhaustive series of tests on Kevlar, subjecting it to UV, thermovac, and atomic oxygen.

TABLE 12

TRACKING

- At the present time, there is not a tracking system that is entirely suitable for position and rate determination of the satellite from the orbiter.
- Tracking can be done using the Orbiter's ku-band radar, but this requires extensive interfacing with the Orbiter system, a situation that is best avoided.
- The satellite does not need to be tracked at a very high data rate: the position of the satellite does not change randomly, and the use of a good computer dynamics model should allow acceptable position determination from a relatively low radar repetition rate.
- If a low repetition rate is used, then it ought to be possible to use a relatively powerful radar--to improve its ranging capability--and still not require an inordinate amount of energy for its operation, on the average. (The panel was told that the Orbiter's ku-band could be a much better radar, if operated at higher power levels.)

TABLE 13

REMOTE TSS OPERATIONS

- The concept of the TSS has been generally that of a tethered satellite released from a manned mothership.
- If a tethered satellite is released from an unmanned spacecraft, some of the operational problems are accentuated.
- One problem, for example, would be the necessity to monitor the entire guidance and control of the satellite from ground stations.
- If it is assumed that the tethered satellite system is flying an atmospheric mission in the Venusion atmosphere, a completely automated system is needed. The time of transmission makes timely human inputs infeasible.
- The tether materials problem will be aggravated significantly in unmanned planetary spacecraft operation.

IV. RECOMMENDATIONS

Most of the tether applications examined by the Technology and Test panel were judged to be feasible and practical. In addition, in each case where data is the product, the ability to obtain such data does not presently exist—the tethered wind tunnel being the prime example. The need for *in situ* data dictates a flight system. The need for this flight system dictates the need for tethers which then dictates requirements for materials and dynamic model code development programs. The development of these two technologies will dictate the pace of tethered system evolution. Final recommendations are listed in Table 14.

TABLE 14

TECHNOLOGY AND TEST RECOMMENDATIONS

- Highly Recommend Aggressive Tether Design Development Program
- Development of Tether Dynamic Codes—User Friendly
- Mission/System Studies Relative to Tethered "Wind Tunnel"
- Definition/Development Studies Relative to Instrumentation
- Concept Feasibility Studies

SECTION III

OVERALL CONCLUSIONS AND RECOMMENDATIONS

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CONCLUSIONS

The workshop gathered together an impressive aray of personalities from industry, academic institutions, and governments to discuss the relatively new area of applied technology of very long tethers in space to a broad spectrum of future space missions: Applications of Tethers in Space.

The initial series of presentations which covered work accomplished to date were well structured and highly informative. Each of the six panels which subsequently went into session covered a major category of tether applications: Electrodynamic Interactions, Transportation, Artificial Gravity, Constellations, Technology and Test, and Science and Applications.

The raw information material produced by the six panels amounted to about 800 pages. These contained new tether applications in space; analyses and assessments of tether applications identified so far with regard to their feasibility, practicality, and to technology requirements; critical issues with regard to design and performance; and, finally, recommendations to NASA for areas of continued work.

A summary appraisal of each panel output is provided in a convenient matrix format (Table 15). It covers the feasibility of key applications, cost benefit and operational potential, technology requirements, design, performance, and operational concerns and critical areas requiring proof of concept tests. A separate matrix (Table 16) shows the areas of the Science and Applications panel and its appraisal of potential mission objectives. In reviewing these assessments, it becomes apparent that certain issues and concerns are common to all categories such as tether materials and dynamic modeling. On the other hand, there appears to be considerable differences particularly in the time frame where useful applications can be envisioned such as between electrodynamic interactions and constellations. Based on these summaries, some preliminary recommendations can be evolved particularly with regard to certain priorities between concepts.

TABLE 15

WORKSHOP PANEL SUMMARY APPRAISALS OF CONCEPT CATEGORIES

8140-83

CATEGORY / PARAMETERS	ELECTRODYNAMIC INTERACTIONS	TRANSPORTATION	CONSTELLATIONS	GRAVITY UTILIZATION	TECHNOLOGY AND TEST
•FEASIBILITY •COST BENEFIT POTENTIAL • OPERATIONAL POTENTIAL	EXCELLENT FEAS. GOOD COST BENEFIT POTENTIAL GOOD OPERATIONAL POTENTIAL	HIGH: P/L BOOST, OTV BOOST ORBITER DEBOOST MEDIUM: ET DEBOOST ORBITER DOCKING P/L BOOST (UPPER STAGE)	FEASIBLE IN LEO COST BENEFITS AND OPERATIONAL POTENTIAL IS CONSIDERABLE	EXCELLENT GOOD COST BENEFIT POTENTIAL GOOD OPERATIONAL POTENTIAL	EXCELLENT FEASIBILITY OF TETHERED "WIND-TUNNEL PROJECT"; GREAT COST BENEFIT AND OPERATIONAL POTENTIAL
•PRINCIPAL TECHNOLOGY REQUIREMENTS	TETHER MATERIALS HIGH VOLTAGE TECHN. ENERGY STORAGE PLASMA CONTACTOR	TETHER MATERIALS TETHER DYNAMICS	NEW SIMULATION MODELS AND CONTROL LAWS	RELIABLE DOCKING & TRANSFER MECHANISMS MALFUNCTION PLANNING ORBIT CORRECTIONS MAINTAINING DESIRED MICROGRAVITY	TETHER MATERIAL DYNAMIC MODELING
ISSUES: •DESIGN •PERFORMANCE •OPERATIONAL	POWER VARIATIONS OVERALL IMPEDANCE RADIATION LOSSES RADIATION DETECTABILITY	UPRATED TETHER HARDWARE PASSIVE DEPL./RETR. USER ACCEPTANCE	STABILITY DEPLOYMENT PROCEDURES MASS EXCHANGE OVERALL LACK OF UNDERSTANDING	FLUID STORAGE TANK DEPLOYMENT DYNAMICS TETHER PLUS ROTATION DYNAMICS MAINTENANCE	IMPROVED SATELLITE TRACKING SYSTEM REMOTE TSS OPERATION
CRITICAL ENGINEERING QUESTIONS	COLLECTION BODY EMITTER PROPERTIES	SYSTEMS DEFINITION	MASS MOVEMENT ALONG TETHERS	NONE MENTIONED SEE "TECHNOLOGY REQUIREMENTS"	GENERATION OF AN ENGINEERING DYNAMIC MODEL
•REQUIRED PROOF OF CONCEPT TESTS	PLASMA CONTACT DEVICES WAVE EMISSIONS & PLASMA PARAMETERS PLASMA WAKES AND DRAG EFFECTS CHARGE EMISSION	NOT DEFINED	TSS DERIVATIVE MISSION CG CONTROLLED ELEVATOR FREE FLYING DEPLOYER-PALLET-END MASS EXPERIMENT	SPACE STATION EXPERIMENTS	IN SITE ENVIRONMENTAL DATA NEEDED
PRIORITY BENEFITS ALTERNATIVES •PRODUCTIVITY •NEAR TERM APPL.	EXCELLENT SCIENCE NO ALTERNATIVES HIGH PRODUCTIVITY EXCELLENT NEAR TERM APPLICATIONS	EXCELLENT EFFICIENCY OVER ALTERNATIVES NEAR TERM APPLIC. TO BOOST SATELLITES	BENEFITS, PRODUCTIVITY AND APPLICATION UNKNOWN AT PRESENT	PRIMARY APPLICATION TO SPACE STATION	KEY TO ALL APPLICATION BENEFITS AND PRODUCTIVITY NEAR TERM EFFORTS REQUIRED

TABLE 16

WORKSHOP PANEL ON SCIENCE AND APPLICATIONS APPRAISAL SUMMARY

5041–83	AERONOMY	GEODYNAMICS	REMOTE SENSING
EXPLOITATION OF EXISTING SYSTEMS	TSS INSTRUMENTATION DIFFERENT INCLINATIONS DIFFERENT LOCAL TIMES DIFFERENT SEASONS POLAR ORBIT	TSS BELOW AND ABOVE ORBITER MAGNETOMETER BOOM GRAVITY GRADIOMETER PRECISION ALTITUDE	TSS WITH OPTICAL IN–STRUMENTS AT LOW ALTITUDE. SPECTRAL AND SPATIAL MEASUREMENTS
EXISTING SYSTEMS WITH MULTIPLE PAYLOADS	MEASUREMENTS OF COM–POSITION CHANGES SEVERAL SATELLITES ON A STRING. MASS SPECTROMETERS, WIND DIRECTION, DENSITY, IONIZA–TION	MULTI–SPACECRAFT TETHER. GRAVITY AND MAGNETIC FIELD GRADIENTS UPWARD AND DOWN–WARD MEASUREMENTS	IDENTICAL INSTRUMENTA–TION ON ORBITER AND SATELLITE MEASUREMENTS AT DIFFE–RENT VIEWING ANGLES.
LOWER ALTI–TUDE MEASURE–MENTS	MEASUREMENT OF MOST IMPORTANT PRO–CESSES BETWEEN 80 AND 130 Km ALTITUDE	GLOBAL OBSERVATIONS IN LOW ALTITUDE	GREATLY IMPROVED RESOLUTION BY LOW ALTITUDE SENSING
TETHERED AUTONOMOUS MULTIPLETS	LONG DURATION MEASURE–MENTS. PLANETARY ATMOSPHERES ROTATING TWO SPACE–CRAFT ABOUT CENTER OF MASS.	PLANETARY MAGNETIC FIELD MEASUREMENTS	———
SUB–TETHER	MEASUREMENTS OF VERTI–CAL STRUCTURE OF ATMOSPHERE	———	———

RECOMMENDATIONS

In order to make useful overall recommendations to NASA planning based on the panel findings and the individual panel recommendations, it will be helpful to derive a listing of priorities among the many concepts and application categories. While much is still unknown and insufficiently understood about the relative merit of one concept or category over others, limited resources dictate that at least a temporary order of priorities be established based on an evaluation of the panel outputs.

In the recommendations, a number of criteria will be applied to the panel findings. Adhering to the following criteria, it is possible to establish preliminary and temporary priorities among the applications.

(1) Needs or special benefits

(2) Tethers are the only way to accomplish the tasks or there are equivalent alternatives

(3) Relative quantity of knowledge or results gained

(4) Feasibility of near-term application.

Priority I: Electrodynamic Interactions

- Provides maximum potential benefit in the power generation mode.
- Alternative approaches appear less efficient and productive.
- Near-term applications have already been initiated in the approved Tethered Satellite System (TSS) project. The initial mission is scheduled for December 1987.

Priority II: Technology and Test
Tether Applications to Transportation

These two categories seem to be next in line and of equal significance. The areas of tether materials and of dynamic simulation technology will remain of fundamental importance across different categories of tether applications for some time. The utilization of tethered aerodynamic models and of tethered momentum transfer modes have no equivalent alternatives and have near to mid-term applications.

Priority III: Tethered Spacecraft Constellations, Gravity Utilization Through Tethers

Constellations so far are the least understood concepts and involve great complexity in their dynamic behavior. Therefore, no near-term applications and benefits have been established. More than any other concept, constellations require several years of analysis and simulation in order to establish their merits. Gravity utilization through tethers other than propellant storage and transfer seems to be deficient in useful applications and cost benefits at this time. This category can ride on the coat tails of other gravity gradient stabilized concepts in order to establish its usefulness.

NASA planning has thus received an important planning tool. The workshop findings have been incorporated into a NASA Program Plan covering several years. Program Plan implementation will certainly result in periodic updating of the workshop recommendations as our understanding of Applications of Tethers in Space increases.

APPENDIX A

PANEL MEMBERS

ARTIFICIAL GRAVITY PANEL

George Butler Co-Chairman	McDonnell Douglas
Bob Freitag Co-Chairman	NASA Headquarters
Dox Doxiadis	Rockwell
Dave Criswell	Calspace
Charles Tang	Jet Propulsion Laboratory
Dennis Fielder	NASA/Johnson Space Center
John Gille	Martin Marietta
Paul Penzo	Jet Propulsion Laboratory
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Joe Tschirgi	McDonnell Douglas
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ELECTRODYNAMIC INTERACTIONS PANEL

Richard S. Taylor Co-Chairman	Smithsonian Astrophysical Observatory
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Roger Williamson	Stanford University
Gerry Murphy	University of Iowa
Uri Samir	NASA/Marshall Space Flight Center and University of Michigan
Marino Dobrowolny	CNR Italy
Don Parks	S-Cubed
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Stan Olbert	MIT
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Ray Schneider	Sperry
George Carignan	University of Michigan
Frederick J. Rich	Air Force Geophysics Lab

CONSTELLATIONS PANEL

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Franco Bevilacqua	Aeritalia - Space Division
Thomas Taylor	TT Associates
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TECHNOLOGY AND TEST PANEL

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Stephen Graff	Jet Propulsion Laboratory
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Klaus Kenhartz	European Space Agency
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Peter H. Broussard	NASA/Marshall Space Flight Center
Nola Engler	University of Dayton
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Dave Christensen	Wyle Laboratories

TRANSPORTATION PANEL

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William Nobles	Martin Marietta
Jerome Pearson	USAF-Flight Dynamics Lab
Milton Contella	NASA/Johnson Space Center

APPENDIX B

AGENDA

APPLICATIONS OF TETHERS IN SPACE WORKSHOP

AGENDA

15-17 JUNE 1983

14 June 1983-Tuesday	
6:00pm - 9:00pm	Registration
15 June 1983-Wednesday	
7:30am - 8:30am	Registration
8:00am - 8:30am	Panel Chairmen Meet
	Session I - Introduction
8:45am - 9:15am	Welcome, Orientation and Purpose...Bob Marshall
9:15am - 10:15am	Keynote Address...Ivan Bekey
10:15am - 10:30am	BREAK
	Session II - Tethered Satellite System (TSS)
10:30am - 10:45am	Project Overview...Jay Laue
10:45am - 11:00am	Tether Deployment System...Donald Crouch
11:00am - 11:30am	Satellite Overview...Gianfranco Manarini
11:30am - 12:00pm	Satellite System Description...Marcello Vignoli
12:00pm - 1:00pm	LUNCH
	Session III - Fundamentals and Applications
1:00pm - 2:00pm	Tether Fundamentals
2:00pm - 2:30pm	Science and Applications
2:30pm - 3:00pm	Electrodynamic Interactions
3:00pm - 3:15pm	BREAK
3:15pm - 3:45pm	Transportation Applications
3:45pm - 4:15pm	Artificial Gravity
4:15pm - 4:45pm	Constellations
4:45pm - 5:15pm	Technology and Test
6:00pm - 7:00pm	NO HOST BAR
7:00pm - 8:00pm	DINNER
8:00pm	Guest Speaker Professor Giuseppe Colombo "Where Are We Going With Tethers?"
16 June 1983-Thursday	Session IV - Panel Meetings
8:00am - 8:30am	Charge to the Panels...Bob Marshall
8:30am - 12:00pm	Panels Meet - Assigned Rooms
12:00pm - 1:00pm	LUNCH
1:00pm - 4:00pm	Panels Meet - Assigned Rooms
4:00pm - 5:00pm	Plenary Session...Preliminary Panel Reports
17 June 1983-Friday	Session V - Panel Meetings Continued
8:00am - 11:00am	Panels Meet - Assigned Rooms
11:00am - 1:00pm	Plenary Session...Final Panel Reports
1:00pm - 2:00pm	LUNCH
	Session VI - Workshop Summary
2:00pm - 3:00pm	Panel Chairmen Meet
3:00pm - 4:30pm	Summary Recommendations of the Workshop
4:30pm	ADJOURN

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